Chemical and Process Engineering Research
ISSN 2224-7467 (Paper) ISSN 2225-0913 (Online)
Vol 4, 2012
www.iiste.org

Drying Characteristics and Mathematical Modelling of Cassava Chips

Ajala, A.S.*, Aboiye, A.O, Popoola, J.O., Adeyanju, J.A.

Department of Food Science and Engineering, Ladoke Akintola University of Technology,
P.M.B. 4000, Ogbomoso, Nigeria
* E-mail of corresponding author: ajlad2000@yahoo.com

Abtract

Cassava chips with dimension 5x2x0.4cm were dried at 600C, 700C and 800C in a laboratory tunnel dryer. Kinetics of drying was investigated using Fick's second law. Drying pattern was observed to be in the falling rate period. Non linear regression analysis was used to fit in the experimental data and the coefficient of determination was found to be greater than 0.97 for all the models. The values of R2, RMSE, MBE and reduced chi square showed that Logarithm model best described the drying behaviour of the samples. The value of activation energy was found to be 30kJ/mol

Key word: cassava chips, tunnel dryer, drying, modelling

Nomenclature

a,b,c,k, k_1, k_2	Drying constant in the model
l	half of the thickness of the sample (m^2)
D_{eff}	effective diffusivity, m^2/s
D_0	pre-exponential factor, m^2/s
E_a	activation energy, kJ/mol
M_0	initial moisture content of the sample (g water/g solid)
M_i	instantaneous moisture content of the sample (g water/g solid)
M_e	equilibrium moisture content of the sample (g water/g solid)
MBE	mean bias error
MR	moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
n	Drying constant in the model
N	number of observation
R	universal gas constant kJ/mol K
RMSE	root mean square error
R^2	coefficient of determination
t	drying time (hr)
χ^2	reduced chi square
z	number of constant in the models

1. Introduction

Cassava (Manihot esculentus crantz) is a popular energy crop consumed in the tropics and in many regions of the world (Ugwu and Odo, 2008). Cassava is the fourth most important energy staple in the tropics and the sixth global source of calories in human diets apart from rice, maize and wheat (FAO, 2004). It ranks the 7^{th} most important crop of the world and constitutes a staple food for about 12.5% of the world's population (Hann and Keyser, 1985). It is a highly important crop in Africa because of its high percentage of carbohydrate and serves as a cheap source of calories for human population and its utilization for industrial purpose such as starch, alcohol, adhesives and livestock feed is yet to be maximally used in Nigeria. (FAO, 2004). Besides serving as the primary staple food for millions of people, it can be converted into dried, stable products such as chips and pellets which are useful as basic raw material in animal feed formulations, ethanol production and cassava beer (Ashaye *et al.,* 2005).

The abundance of cassava tubers and its myriads economic importance calls for thorough research on the product. Cassava chips are the most common form in which dried cassava root are marketed and most exporting countries produce them, it is a rich source of cassava pellet, alcohol, industrial starches and cassava beer (Wheatly *et al.,* 1995). The cassava tubers are peeled and sliced to irregular shapes which vary in sizes after which they are dried and stored in silos; they are produced extensively in Thailand, Malaysia, Indonesia, some part of Africa and some parts of European countries (Tewe, 1994; Wheatly *et al.,* 1995 and FOS, 2000). In Nigeria, since cassava has high moisture content, the chips are subjected to drying traditionally using heat from sun but this method requires much time which may result to spoilage organism attack as well developing off- flavour on storage after drying. Because of this problem, there is need to develop an effective drying technology to convert the product into stable form for industrial and export purposes. The objective of the study is to use mechanical drying system to convert raw cassava roots to dried cassava chips which can be stored and preserved as raw material for production of value added product such as starch and ethanol. However, to achieve this purpose, there is a need to develop mathematical model which can predict accurately the drying behaviour of sample in the dryer. Therefore a mathematical model anchored on drying kinetics which normally based on the physical mechanisms of internal heat and mass transfer to the material being dried which controls the process resistance as well as on structural and thermodynamic assumptions must be modelled.

2. Materials and Methods

(a)Drying Experiment

Cassava tubers used for the experiments were procured from Ladoke Akintola University Teaching and Research Farm. The tubers were peeled with a stainless knife and cut into chips of dimension 5cmx2cmx0.2cm using vernier caliper. The chips were loaded into the tunnel dryer for drying process. The dryer was built in the Department of Food Science and Engineering, Ladoke Akintola University of Technology, Ogbomoso Nigeria. The dryer was installed in an environment of 50% relative humidity and 30^0C. Steady state of temperatures was achieved in the dryer before the chips were loaded. The drying process was performed at 60^0C, 70^0C and 80^0C. The samples were removed from the dryer and weighed manually at one hour interval to monitor moisture loss. Drying process was truncated when two consecutive sample weights remained constant.

(b)Mathematical model

In this work, a simplified Fick's second law of diffusion was adapted for moisture diffusion which is governed by equation 1

$$\frac{\partial w}{\partial t} = D_{eff}\frac{\partial^2 w}{\partial t^2} \qquad 1$$

Where w is the local moisture content (g water/g mass), t is the drying time (s), x is length (m), D_{eff} is the diffusion coefficient in solid (m^2/s). The following assumptions were made. (a) the food sample was one-dimensional (b) the initial moisture content was uniform throughout the solid.

To determine the drying characteristics of the chips, the experimental data were fitted into six different models as presented in Table 1. These models described the relationship between moisture loss and drying time with various coefficients attached to each model.

Table 1: Mathematical drying models

Models	Equation	References
Henderson and Pabis	MR=aexp(-kt)	Chinnman, (1984)
Logarithms	MR=aexp(-kt) +c	Togrul and Pehlivan, (2003)
Newton	MR=exp(-kt)	Kingly et al., (2007)
Page	MR=exp(-kt^n)	Karathanos and Belessiotis, (1999)
Two term	MR=a exp(k$_1$t) + b exp(k$_2$t)	Hodge & Taylor, (1999)
Wang and Sing	MR= 1+ at+ bt^2	Wang and Singh, (1978)

(c)Statistical Analysis

The constants of each model were estimated using a non-linear regression analysis performed using Statistical Package for Social Scientist (SPSS 15.0 versions) software. Statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE) and mean bias error (MBE) were used to test the reliability of the models. A good fit is said to occur between experimental and predicted values of a model when R^2 is high and χ^2, RMSE and MBE are lower (Demir *et al.,* 2004). The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero (Gohank *et al.,* 2009). The comparison criteria method was determined using equations 2, 3 and 4:

$$\chi^2 = \frac{\sum_{i-1}^{n}(MR_{(\exp,i)} - MR_{(pred,i)})^2}{N-z} \qquad 2$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{n}(MR_{(pred,i)} - MR_{(\exp,i)}) \qquad 3$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{(pred,i)} - MR_{(\exp,i)})^2\right]^{1/2} \qquad 4$$

(d) Determination of moisture diffusivity

The simplified equation of Fick's law of moisture diffusion was adapted to determine the effective moisture diffusion from the samples during drying. For slab geometry, equation 1 was simplified to form equation 5 according to Srikiatden and Roberts, (2005) which is represented thus:

$$\text{MR} = \frac{M - M_0}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{n=1}\frac{1}{(2n-1)^2}\exp\frac{-(2n-1)^2\pi^2 D_{eff}t}{4l^2} \qquad 5$$

Where D_{eff} is the moisture diffusivity (m^2/s), t is the drying time (s), l is the half of the slab thickness (m), MR= dimensionless moisture ratio, Mi = instantaneous moisture content (g water/g solid), M_e =equilibrium moisture content (g water/ g solid), Mo = initial moisture content (g water/ g solid). However, due to continuous fluctuation of relative humidity of the drying air in the dryer, equation 5 is simplified in equation 6 according to Dimente and Munro, (1993) and Goyal *et al.,* (2007)

$$\text{MR} = \frac{M_i}{M_O} = \frac{8}{\pi^2}\sum_{n=0}^{n=1}\frac{1}{(2n-1)^2}\exp\frac{-(2n-1)^2\pi^2 D_{eff}t}{4l^2} \qquad 6$$

The effective moisture diffusivity (D_{eff}) was calculated from the slope of plot of ln MR against drying time (t) according to Doymas, (2004) and is represented in equation 7

$$k = \frac{D_{eff} t}{4l^2} \quad 7$$

Where k is the slope.

The model that best described the drying behaviour of the samples was used to evaluate the moisture diffusivity of the samples.

(e) Determination of Activation Energy

The effect of temperatures often affects the effective moisture diffusivity of the product during drying. The correlation of temperature and moisture diffusion is inversely related as expressed using Arrhenius equation.

$$D_{eff} = D_0 \exp \frac{-E_a}{RT}$$

Where D_0 is the pre-exponential factor of the Arrhenius equation in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol K and T is the absolute air temperature in K. The activation energy was calculated by plotting the natural logarithm of D_{eff} against inverse of the absolute temperature. Detail of the plot is found in Figure 3

3. Results and Discussion

(a)Drying Assessment of the Chips

The drying behaviour of the chip is shown in Figure 1. The curve exhibited falling rate period which often is the characteristics of most agricultural products as reported by Karel and Lund, (2003); Ramaswamy and Marcotte, (2006) Velic *et al.,* (2007) and Ajala *et al.,* (2012). Samples dried at 60^0C and 70^0C exhibited a single falling rate but it was however observed that sample dried at 80^0C exhibited a second falling rate period when moisture loss was 1.76 g water/g solid and drying time was 3 hours. By comparing the gradient of the two falling rate period, it was observed that the first falling rate had the steepest gradient (from moisture content of 4.50 g water/ g solid to 1.76 g water/ g solid in three hours) compared with the second falling rate period (0.91 g water/ g solid to 0.19 g water/ g solid in six hours). The reason for higher moisture removal in the first falling rate was that moisture percentage was higher in the sample for drying at the initial stage. This observation was earlier reported by Ajala *et al.,* (2011).

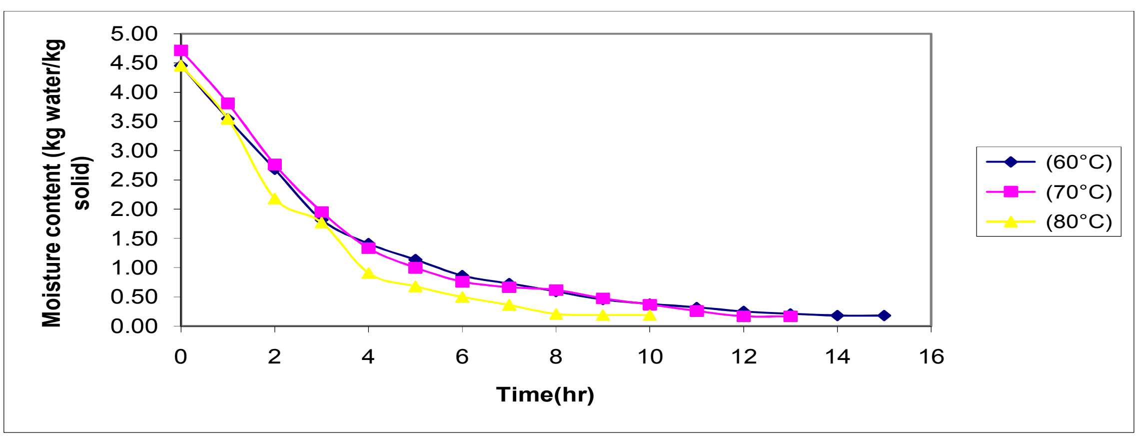

Figure 1: moisture content against time

The effect of temperatures on the moisture ratio of the chips is shown in figure 2. The figure showed that increase in temperature increased drying rate hence reduced drying time. For instance, it took 10 hours to reduce moisture from 1.00 to 0.04 for sample dried at 80^0C; drying took 13 hours to reduce moisture from 1.00 to 0.04 for samples dried at 70^0C and it took 15 hours to reduce moisture from 1.00 to 0.04 for chips dried at 60^0C. From this analysis, temperature seemed to play a major factor in the drying of the samples as well as other agricultural produce as reported by Abraham *et al.,* (2004). Drying was faster at 80^0C because there was higher heat transfer to the sample and consequently higher mass transfer of moisture from the sample which resulted in lower drying time as reported by Aghbashlo *et al.,* (2009)

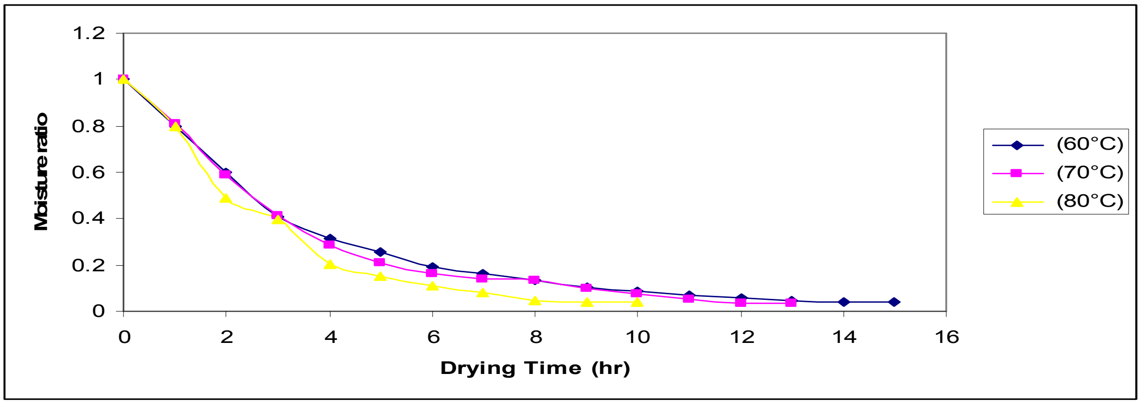

Figure 2: Moisture ratio against time

(b) Models Evaluation using statistical criteria

Table 1 and 2 show the statistical and constant values for all the models tested respectively. In all the models, the values for R^2 were greater than 0.986 in all which proved that all the six models gave good fit to the experimental data. A good fit occurred when R^2 is high and reduced chi square, MBE and RMSE are low (Ahmet *et al.,* 2007). The highest value R^2 was 0.997 found in Logarithms model while the lowest value was 0.953 found in Wang and Sing model. The lowest value of reduced chi square was 0.0002 found in Logarithms model while the highest value was 0.0044 found in Wang and Sing model. Therefore Logarithms model was considered the best model in the present study to represent hot air drying characteristics of cassava chips and hence it was used further to determine the values for effective diffusivities of moisture transfer during the drying process of the chips. The detail values of constants of the models were presented in Table 2; constant *'a'* had highest and lowest values of 1.052 and -0.248 found in Logarithms and Wang and Sing models respectively; constant *'b'* had the highest and lowest values of 0.218 and 0.008 found in Two-Term models. The values for constant *'c'* were 0.029, 0.025 and -0.017 found in Logarithms model while the highest and lowest values for constant 'k' were 0.358 and -0.277 found in Henderson and Pabis and Page models respectively. The values for 'k_1' in Two-term were 0.292, 0.306 and 0.358 while the values for 'k_2' were -0.014, -0.096 and 0.358. Furthermore, the values for constant 'n' were 0.973, 1.032 and 1.182.

Figure 3 showed the comparison of experimental moisture ratio to predicted moisture ratio obtained from Logarithms model. The figure pictured a good agreement between the predicted and experimental data which implied that Logarithms model is suitable to describe the drying process of the chips using tunnel dryer in the range of the experimental design.

(c) Determination of Effective Moisture Diffusivity

The values of moisture effective diffusivity are shown in Table 4; it ranged from $2.43x10^{-11}$ at 60^0C, $3.45x10^{-11}$ at 70^0C and $4.52\ x10^{-11}$ at 80^0C. The data showed that moisture diffusion is temperature dependent. The value of D_{eff} increased as the temperature increased.

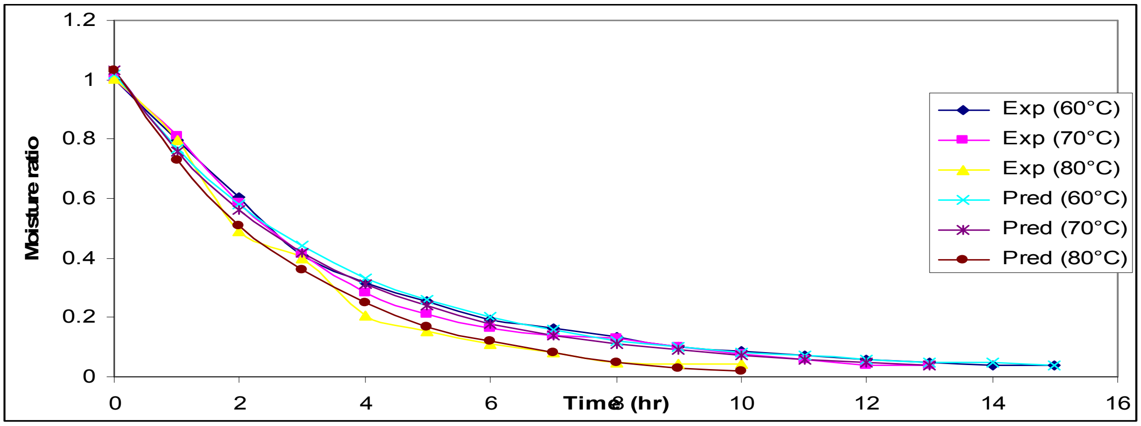

Figure 3 Experimental and predicted moisture ratio against time

This was because moisture lost faster at higher temperatures than lower temperatures. The same observation has been reported by Hawlander *et al.,* (1991), Belghit *et al.*, (1999), Abraham *et al.,* (2004) and Guine *et al*., (2009). The values of moisture diffusivity in this study was in the range of food products (10^{-7} to 10^{-12}) as reported by Hii *et al*., (2009). However, the values were less than the values of pretreated cassava chips reported by Tunde-Akintunde and Afon, (2009) which was (7.31 x 10^{-7} m^2/s to 8.06 x 10^{-7} m^2/s). The reason could be because of varied cultivars or that the effect of pretreatment induced and increased the diffusion rate of moisture in the samples. Furthermore, the values were in agreement with other research work such as Doymas, (2004) with value of 4.26x10^{-11} m^2/s for garlic slices.

Table 2: Values of statistical parameters

Model	Temp	R^2	χ^2	MBE	RMSE
Henderson	60	0.995	0.0004	-0.0059	0.0200
and Pabis	70	0.993	0.0006	-0.0048	0.0241
	80	0.989	0.0011	0.0017	0.0310
Logarithms	60	0.997	0.0002	0.0009	0.0140
	70	0.994	0.0006	0.0008	0.0218
	80	0.989	0.0013	-0.0018	0.0305
Newton	60	0.995	0.0004	-0.0059	0.0197
	70	0.992	0.0006	-0.0063	0.0249
	80	0.987	0.0012	-0.0019	0.0338
Page	60	0.996	0.0004	-0.0047	0.0197
	70	0.992	0.0007	-0.0077	0.0250
	80	0.993	0.0008	--0.0073	0.0259
Two terms	60	0.998	0.0003	0.0016	0.0148
	70	0.994	0.0006	0.0001	0.0219
	80	0.989	0.0015	0.0017	0.0310
Wang and	60	0.953	0.0044	0.0134	0.0624
Sing	70	0.964	0.0035	0.0027	0.0551
	80	0.985	0.0019	-0.0007	0.0392

(d) Activation Energy

Figure 4 shows the activation energy which was determined by the plot of natural logarithm of effective diffusivity (lnDeff) against the inverse of absolute temperature (1/T). The gradient of the curve gave the value of activation energy (E_a) to be 30.30kJ/mol and diffusivity coefficient (D_0) to be 1.39x$10^{-6}$$m^2/s$. The value of activation energy in this study is comparable with other research work. For instance, the value is greater than Bon *et al.*, (1997) report on potato which was 20kJ/mol. It is also greater than that of Doymaz, (2004) report on carrot which was 28.36 kJ/mol but less than the value got by Park *et al.,* (2002) for mint leaves which was 82.93 kJ/mol and also less than that of

Mazza. and Lemaguer, (1980) on onion which was 57 kJ/mol. The value of diffusivity constant (D_0) in this work is less than the value reported by Kuitche *et al.,* (2007) which is 1.8x10^{-5}m^2/s for pretreated okra but it is in agreement with the value reported by Hii *et al.,* (2009) which is 4.08x10^{-6}m^2/s for cocoa. The variation in the values definitely could be as a result of different species of products being considered.

Table 3: Values for model constants

Model	Temp	a	b	c	k	k_1	k_2	n
Henderson and Pabis	60	1.006			0.267			
	70	1.002			0.290			
	80	1.040			0.358			
Logarithms	60	0.991		0.029	0.294			
	70	1.007		0.025	0.313			
	80	1.052		-0.017	0.342			
Newton	60				0.266			
	70				0.284			
	80				0.345			
Page	60				-0.277			0.973
	70				-0.271			1.032
	80				-0.276			1.182
Two terms	60	0.996	0.024			0.292	-0.014	
	70	1.023	0.008			0.306	-0.096	
	80	0.821	0.218			0.358	0.358	
Wang and Sing	60	-0.179	0.008					
	70	-0.199	0.010					
	80	-0.248	0.016					

Table 4: Values of effective moisture diffusivities at different temperatures

Drying air velocity (m/s)	Drying air temperature (^{0}C)	Effective moisture diffusivity (m^2/s) (D_{eff}x 10^{-11})
2.1	60	2.43
2.1	70	3.45
2.1	80	4.52

Determination of Activation Energy

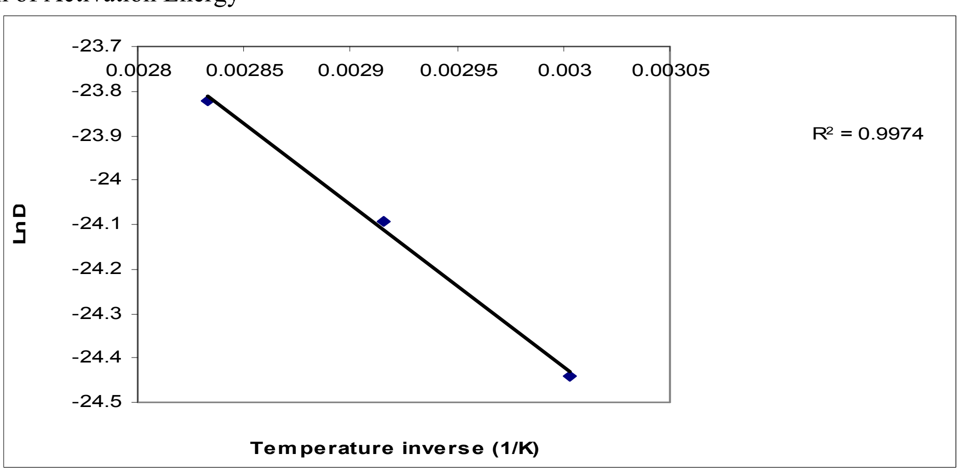

Figure 4: Plot of ln D_{eff} against Temperature Inverse

4. Conclusion

Cassava chips were dried in a convectional tunnel dryer at three temperatures 60^0C, 70^0C and 80^0C. From the experimental analysis, it was observed that drying took the single falling rate period except at 80^0C where samples experienced second falling rate period. Also temperature played an important factor in removing moisture in the samples; at higher temperature of 80^0C, samples dried faster than at 60^0C. The effective moisture diffusivity of the sample was within the range of agricultural produce and it increased as temperature increased. The activation energy of the sample was comparable and was within the range of other agricultural product. Fick's law of diffusion for thin layer drying can be used to model drying characteristics of cassava chips in tunnel dryer

References

Abraham, D.G., Arolilo, A.P., Rosimeire, M.R., Cala, S.S.L., and Amanda, C.F. 2004. The air drying behaviour of osmotically dehydrated jackfruit. Proceeding 14th int. drying symposium, pp1-3

Aghbashlo, M. Kianmehr, M.H. Khani, S and. Ghasemi, M (2009). Mathematical modelling of thin-layer drying of carrot, Institute of Agrophysics, Polish Academy of Sciences journal, *23, 313-317*

Ahmet, C., Kamil K. and Oktay H. (2007). Modelling of intermittent drying of thin layer rough rice. Journal of Food Engineering 79: 293–298

Ajala, A.S, Falade, K.O. and Tunde- Akintunde T.Y. (2011). Effect of osmotic pretreatment on the drying kinetics of okra (*Hibiscus ecsulentus*). Journal of Engineering and Technology,vol.6 (2): 41- 44

Ajala, A.S. Ajala, F.A. and Tunde-Akintunde, T.Y. (2012). Study on Drying Kinetics of Fermented Corn Grains. Food Science and Quality Management Journal Vol 5: 10-17

Ashaye,O.A., Adegbulugbe, T.A. and Dawodu, O.J (2005). Evaluation of the Processing Technologies of Cassava Chips and Flour in Oyo and Ogun States of Nigeria. World Journal of Agricultural Sciences 1 (1): 56-58Belghit, A., Kouhila, M. and Boutaleb, B.C. (1999). Experimental study of drying kinetics of sage in a tunnel working in forced convection. Rev. Energy, vol.2:17-26

Belghit, A., Kouhila, M. and Boutaleb, B.C. (1999). Experimental study of drying kinetics of sage in a tunnel working in forced convection. Rev. Energy, vol.2:17-26

Bon, J., S. Simal, C. Rossello and A. Mulet, 1997. Drying characteristics of hermispherical solids. J. Food Eng., 34: 109-122

Chinnman 1984. Evaluation of selected mathematical models for describing thin layer drying of in-shell pecans. Transaction of the ASAE, 27: 610-615

Demir, V., Gunhan, T., Yagcioglu, A.K. and Degirmencioglu, A. 2004. Mathematical modeling and the determination of some quality parameters of air dried bay leaves. Biosystems Engineering, 88: 429-437

Dimente, L.M. and Munro, P.A 1993. Mathematical modeling of thin layer solar drying of sweet potato slices. Solar Energy, 51(4):271-276

Doymaz, I. 2004. Convective air drying characteristics of thin layer carrots. *Journal of Food Engineering*, vol. 61, 2004, no. 3, p. 359-364.

FAO., 2004. Online statistical database Rome, Italy Food and Agriculture Organization of the United Nations (www.fao.org)

Federal Office of Statistics, 2000. Annual Report, (FOS) Abuja

Gökhan G., Necdet Ö. and Ali G. (2009). Solar tunnel drying characteristics and mathematical modelling of tomato. J. of Thermal Science and Technology, 29(1): 15-23

Goyal, R.K., Kingsley, A.R.P., Manikantan, M.R., and Ilyas, S.M. 2007. Mathematical modeling of thin layer drying kinetics of plum in a tunnel dryer. Journal of Food Engineering 79(1): 176-180

Guine, R., Lopes, P., Joao, B.M. and Ferreira, D.M.S 2009. Effect of ripening stage on drying kinetics and properties of S. Bartolomeu pears. International Journalof Academic Research, vol.1 no 1, p3

Hahn, S.K. and Keyer, J. (1985). Cassava: A basic food for Africa. Outlook Agriculture, 14: 9: 5-9.

Hawlander, M.N.A., Uddin,M.S., Ho, J.C. and Teng A.B.W. 1991. Drying characteristics of tomatoes, Journal of Food Engineering, 14: 249-268

Hii, C.L., Law, C.L. and Cloke, M. (2009). Modeling using a new thin layer drying model and product quality of cocoa. Journal of Food Engineering 90: 191–198

Hodge, B. K. & Taylor, R. P. (1999) Analysis and Design of Energy Systems, 3rd Ed., Prentice Hall Inc., New Jersey,

Karathanos, V.T. & Belessiotis, V. G. (1999). Application of a thin layer equation to drying data of fresh and semidried fruits. Journal of Agricultural Engineering Research, 74, 335-361,

Karel, M and Lund, D. B 2003 : Physical Principles of Food Preservation. New York: Marcel

Kingly, R.P., Goyal, R.K., Manikantan, M.R. and Ilyas, S.M. 2007. Effect of pretreatment and drying air temperature on drying behaviour of peach slice. International Journal of Food Science and Technology, 4:65-69

Kuitche, A., Edoun, M. and Takamte, G. (2007). Influence of Pre-treatment on Drying on the Drying Kinetic of A Local Okro (Hibiscus ersculentus) Variety. World Journal of Dairy & Food Sciences 2 (2): 83-88,

Mazza, G. and M. Lemaguer, 1980. Dehydration of Onion: Some theoretical and practical considerations. J. Food Technol., 15: 181-194.

Park, K., Vohnikova, Z. and Vrod, F.P. 2002. Evaluation of drying parameters and desorption isotherms of garden mint leaves. J. Food Eng.

Ramaswamy, H.; Marcotte, M. 2006. Food Processing - Principles and Applications. London: Taylor and Francis Group.

Srikiatden, J. And Roberts, J. S. 2005. Moisture Loss Kinetics of Apple during Convective Hot Air and Isothermal Drying. International Journal of Food Properties 8.: 493-512

Tewe, O. (1994). Indices of cassava safety for livestock feeding. Acta Horticulture, pp241-249

Togrul, I.T., Pehlivan, D., 2004. Modeling of thin layer drying of some fruits under open-air sun drying process. Journal of Food Engineering 65, 413–425.

Tunde-Akintunde T.Y. and Afon A.A, (2009). Modelling of Hot-Air Drying of Pretreated Cassava Chips. Agricultural Engineering International: the CIGR Ejournal. Manuscript 1493 Vol. pp 1-7

Ugwu, F.M.and Odo, M.O. (2008) Effect of Cassava Variety on the Quality and Shelf Stability of Soy-Garri. Pakistan Journal of Nutrition 7 (2): 381-384,

Velić, D., Bilić, M., Tomas, S., Planinić, M., Bucić-Kojić, A. and Aladić, K. 2007. Study of the Drying Kinetics of "Granny Smith" Apple in Tray Drier, Agric. conspec. sci. Vol. 72 (4): p 326

Wang C.Y. and Singh R.P., 1978. A Single Layer Drying EquationforRoughRice.ASAEPress,St.Joseph,MI,USA

Wheatly, C., Gregory J., Scott, J., Best, R. and Siert, W. (1995). A manual on product development. Adding value to root and tuber crops. IITA, Ibadan:4